Demonstration of the Surface Stabilized Combustor for Advanced Industrial Gas Turbines

Distributed Energy Resources Peer Review

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Project Goals

Develop a commercially viable low-emissions combustion system for industrial gas turbines.

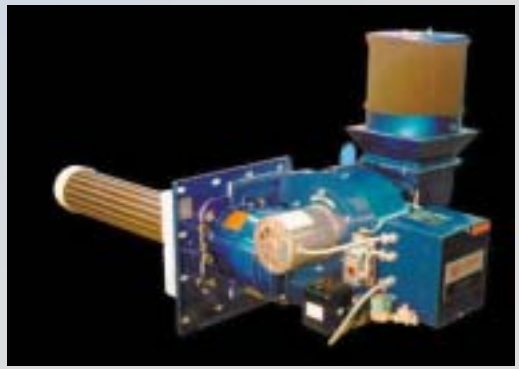
- < 3-ppm NO_X (15% O_2)
- < 10-ppm CO (15% O_2)
- < 10-ppm UHC (15% O_2)
- 90 to 100% load operating range
  - Stretch goal 60 to 100% load operation
- 4% combustor pressure drop
  - Stretch goal 3% combustor pressure drop

Our Partners

- **Solar Turbines**
- **US Department of Energy**, Distributed Energy Resources
- **California Energy Commission**, Public Interest Energy Research

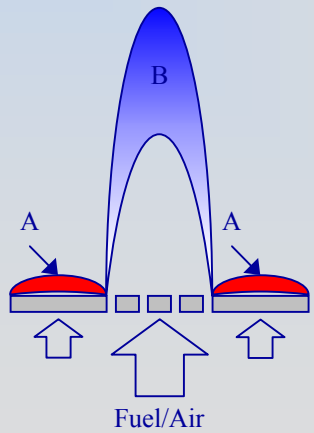
Technology Approach

- Adapt successful CSB microSTAR™ technology to Gas Turbine service – nanoSTAR
- Lower NO_X emissions than aerodynamically stabilized lean premixed injector
- Enhanced lean stability
- Compatible with annular, can-annular and external can gas turbine combustors
- Single combustion zone
- No extraordinary control scheme

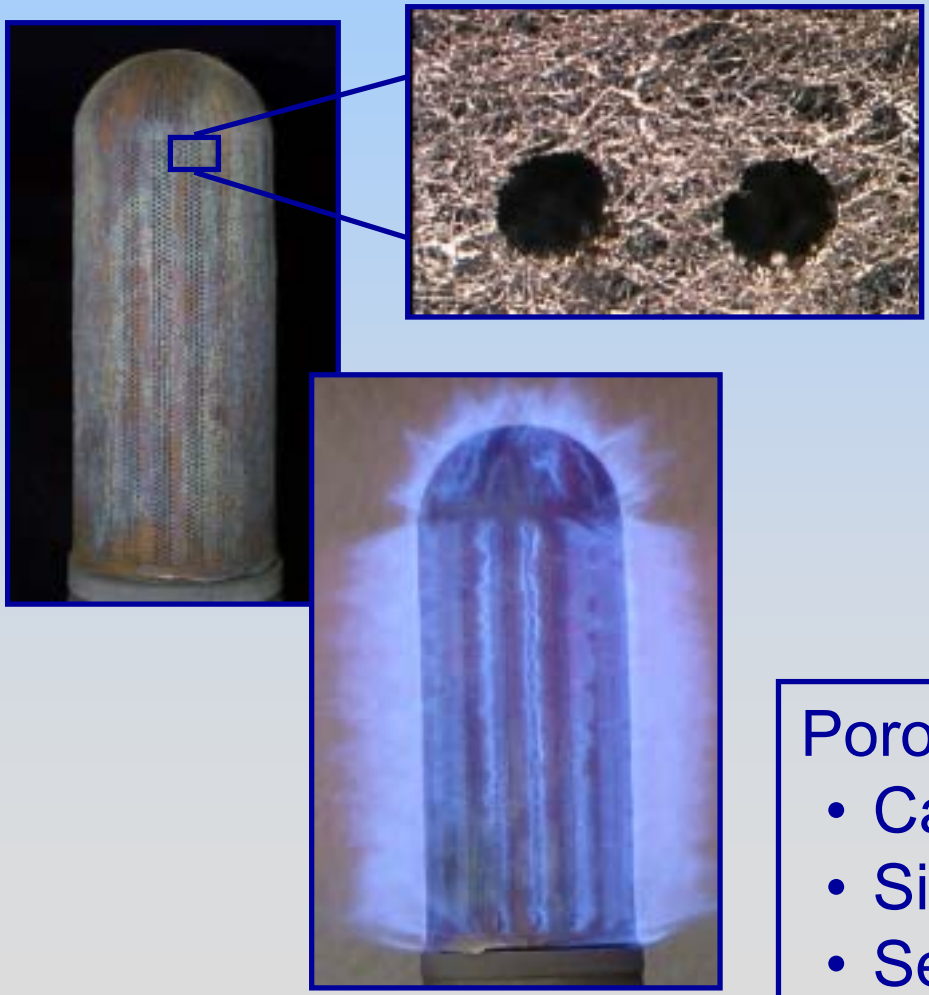


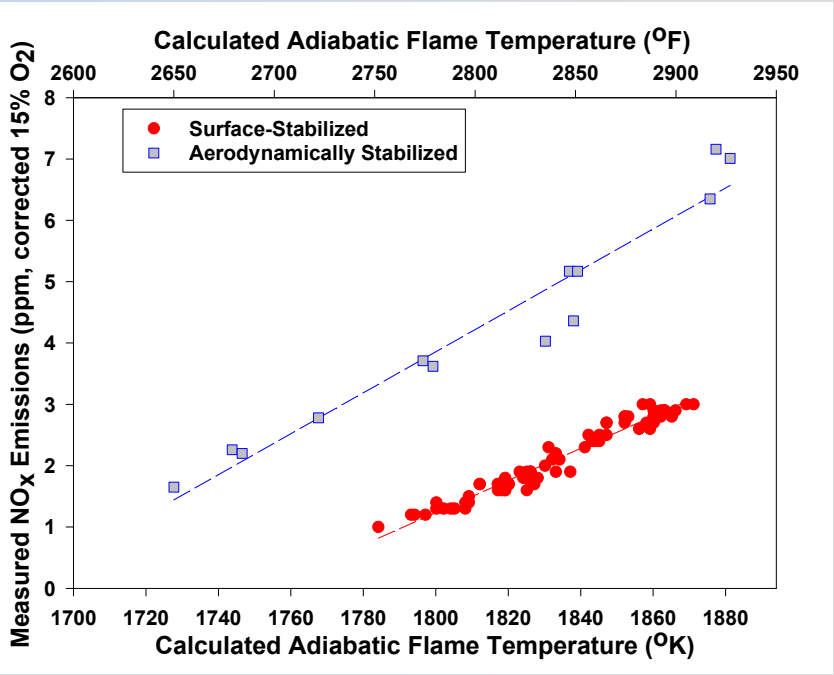
Technology

- Porous Surface is selectively perforated to achieve radiant and stabilized laminar blue flame regions
- Dry Low NO_X with high volumetric heat release
  - Surface Firing Rate of 1,000,000 Btu/hr-ft^2-atmosphere
  - At 10:1 Pressure Ratio and 10,000 Btu/hr-kW Heat Rate Yields 1 Megawatt Per Square Foot of Surface



Technology

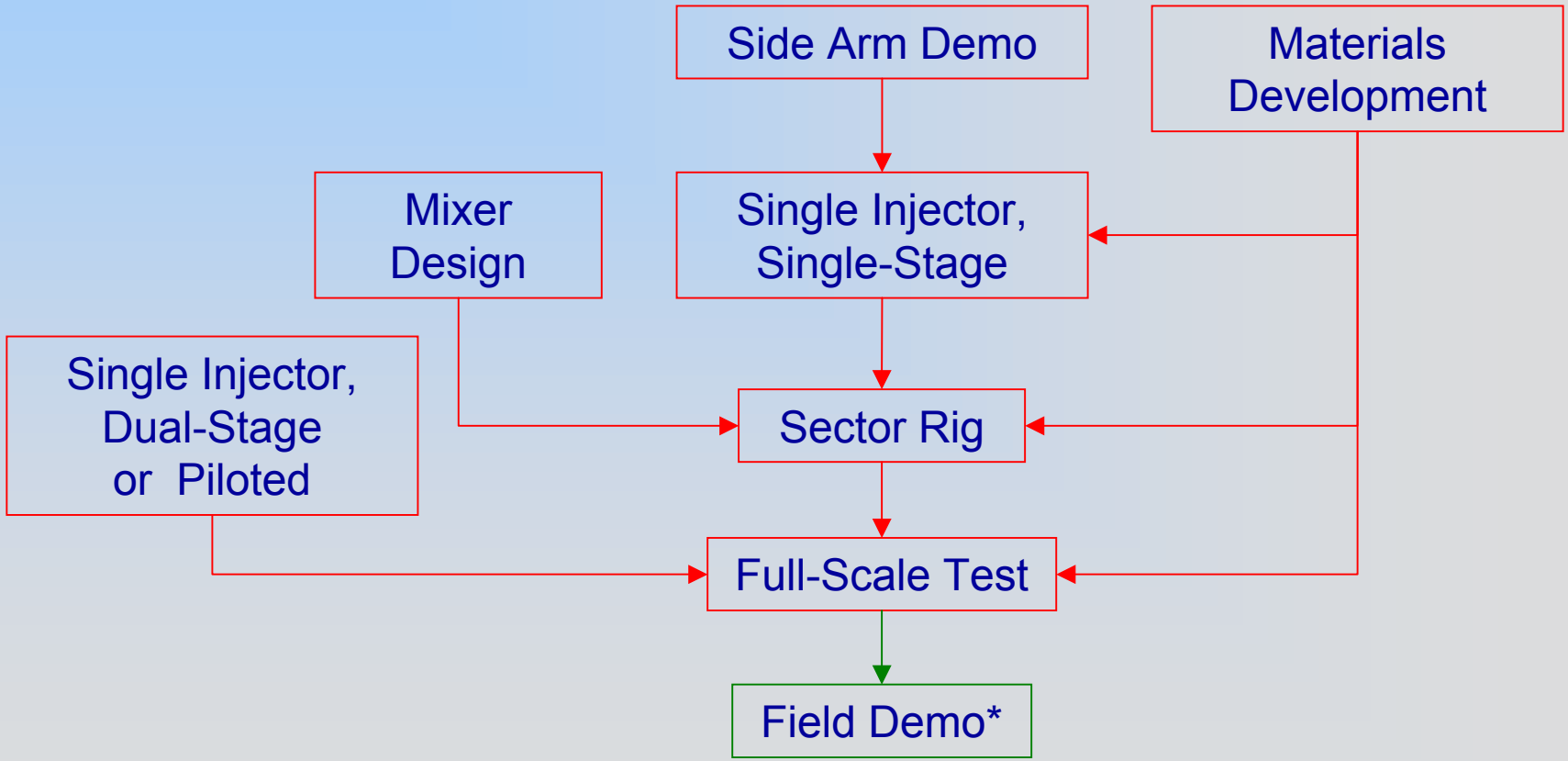




Porous Metal Fiber Pad

- Cast into 3-D Shape
- Sintered
- Selectively Perforated

Technical Development Path

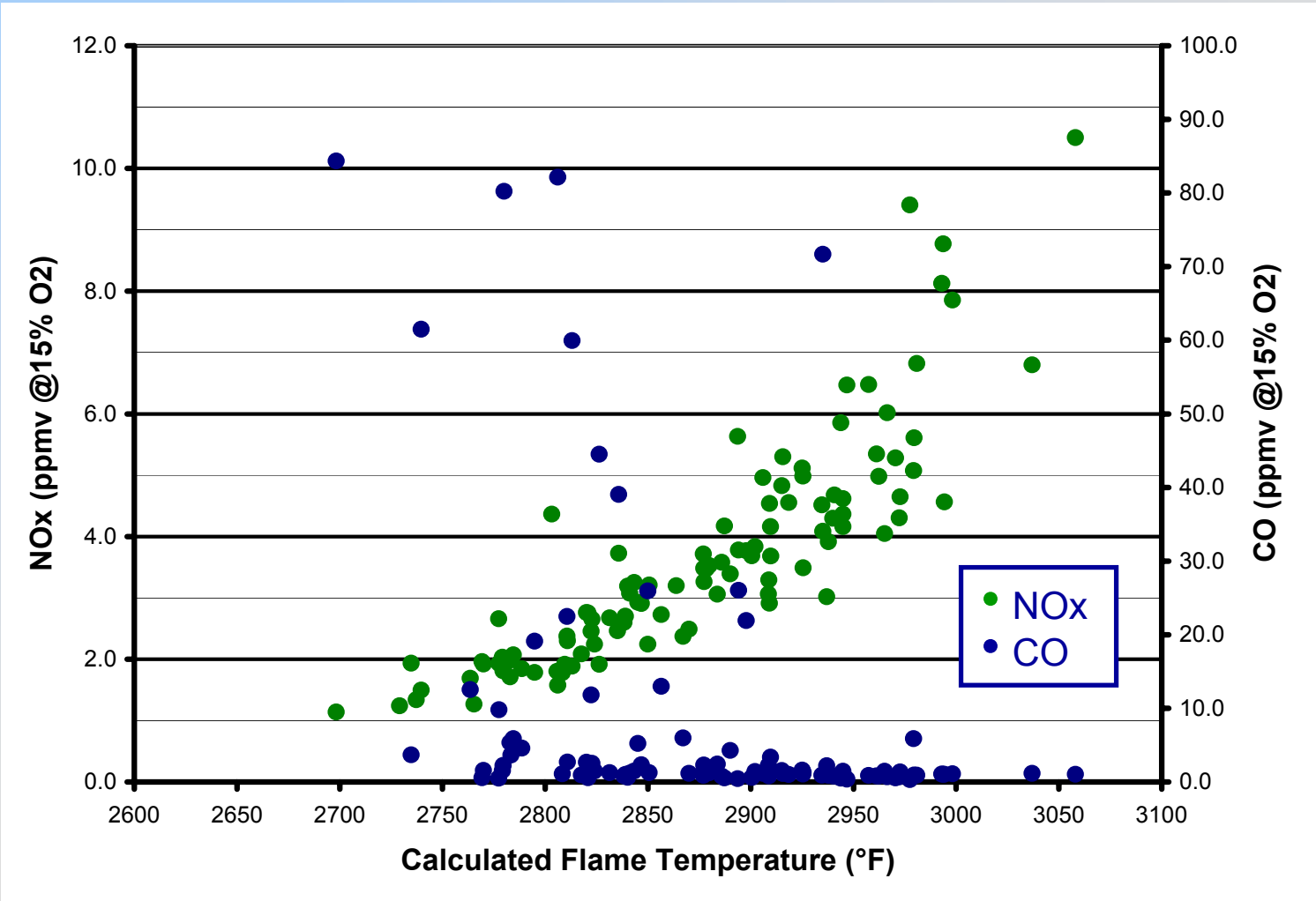


*Beyond Scope of Current Project

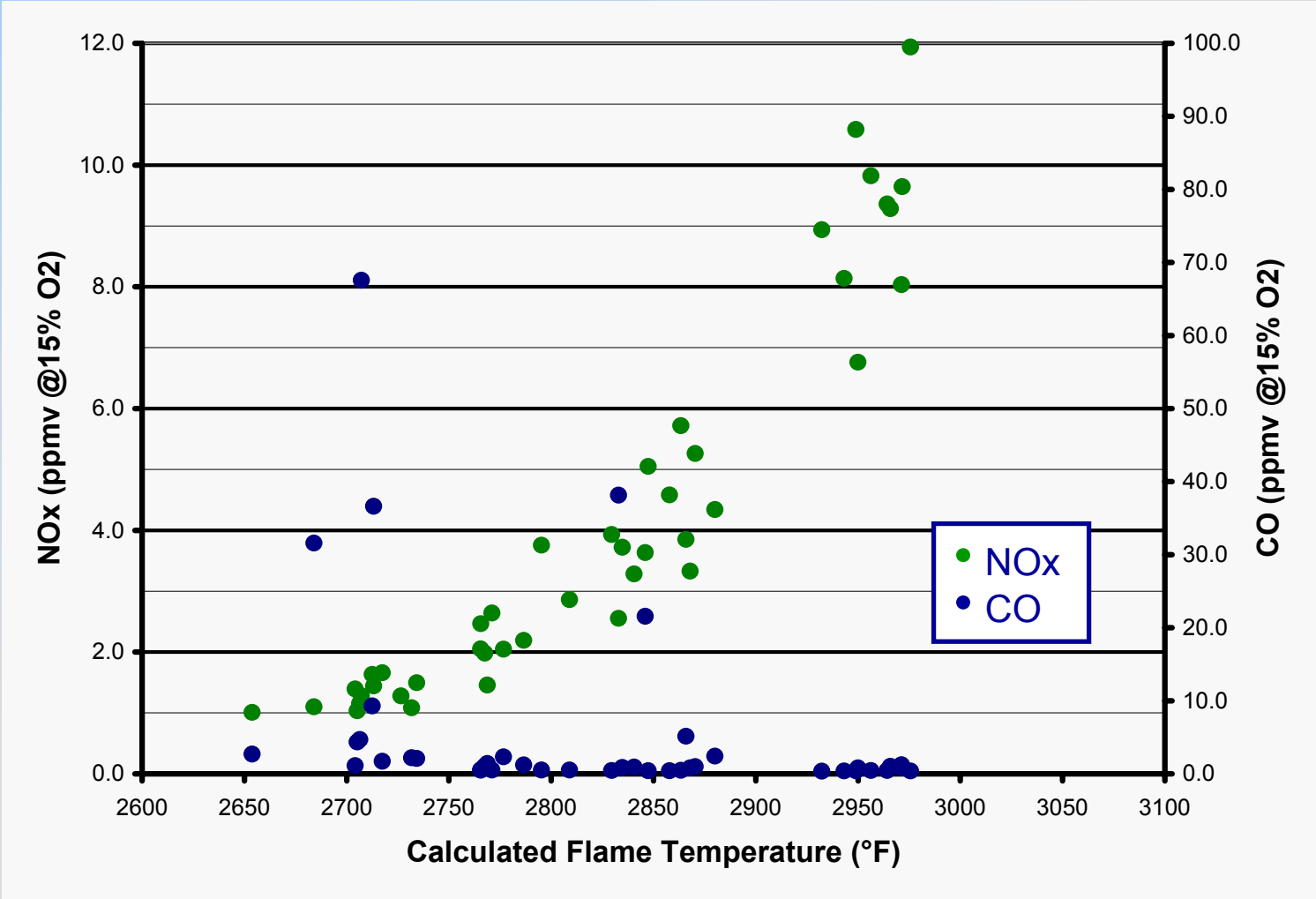
Overview

- Select Milestones
  - ✓ Saturn Demonstration – Completed 6/01
  - ✓ Cast Taurus 60 Injector – Completed 10/01
  - ✓ Correct Poor Flow Distribution – Completed 11/01
  - ✓ In-house Casting Process Development – Completed 2/02
  - ✓ Mixer Concept Screening Tests – Completed 2/02
  - ✓ Single Injector Tests – Completed, 8/02
  - ✓ **Multiple Injector, Sector Tests – Completed, 11/02**
  - ✓ **Multiple Zone Injector Tests – Completed, 3/03**
  - ✓ **Full Annular, Full-Scale Tests – Completed, 10/03**

700 °F / 12 atm
Single Injector Testing



800 °F / 17 atm
Single Injector Testing

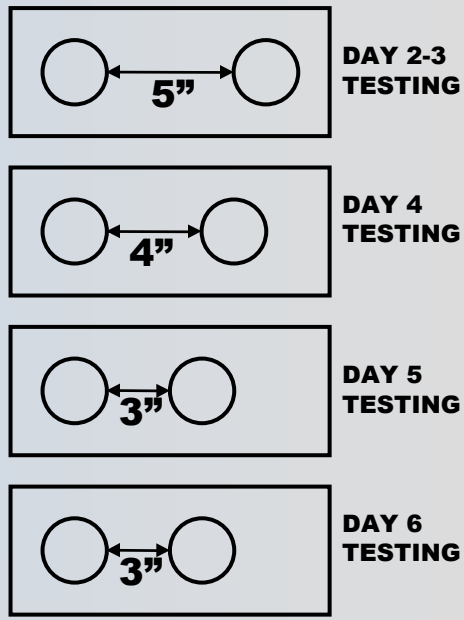


Summary

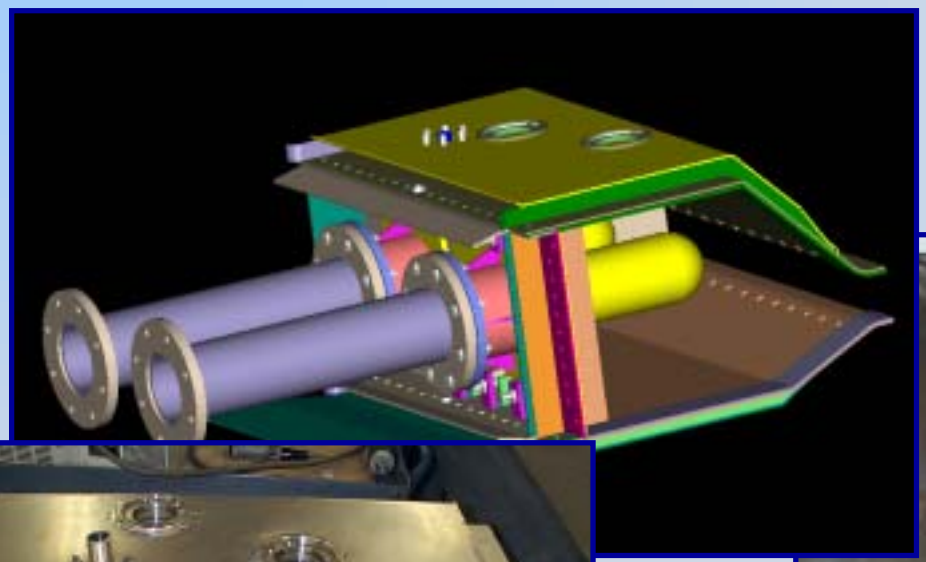
- Low NO_X (down to 1 ppm @ 15% O_2) performance was demonstrated at full-load pressure and combustion air inlet temperatures.
- A broad range of Surface Firing Rates (0.6 – 1.7 MMBtu/hr-ft^2-atm) were demonstrated at pressures up to 17 atmospheres.
- Developed design criteria for flow split between perforated and non-perforated regions
- Injectors technology ready to move forward with system development

Multiple Injector Tests "Sector Rig"

- Objectives
  - Demonstrate ability of injectors to operate in close proximity
  - Characterize crossfire ignition of injectors at a variety of inlet temperatures and pressures
  - Evaluate effect of injector separation distance on emissions performance
  - Identify interactions between injectors



Sector Rig Hardware



Sector Rig Results

Testing	# of ignitions	Pressures (atm)
Day 3	5	1.3, 2.1, 3.6, 4.8, 6.5
Day 4	8	2.2, 3.1, 4.2, 5.9, 6.8, 7.9, 8.9, 10.0
Day 5	7	1.7, 2.2, 3.3, 3.4, 4.5, 6.9, 7.7
Day 6	2	7.4, 9.6

- Pressurized Ignition
  - Smooth and repeatable
  - Injector separation did not affect ignition behavior
  - No observable combustion dynamics or pressure oscillations for nominal and low SFR conditions
  - Transient pressure oscillations observed during ignition at high SFR condition

Sector Rig Results

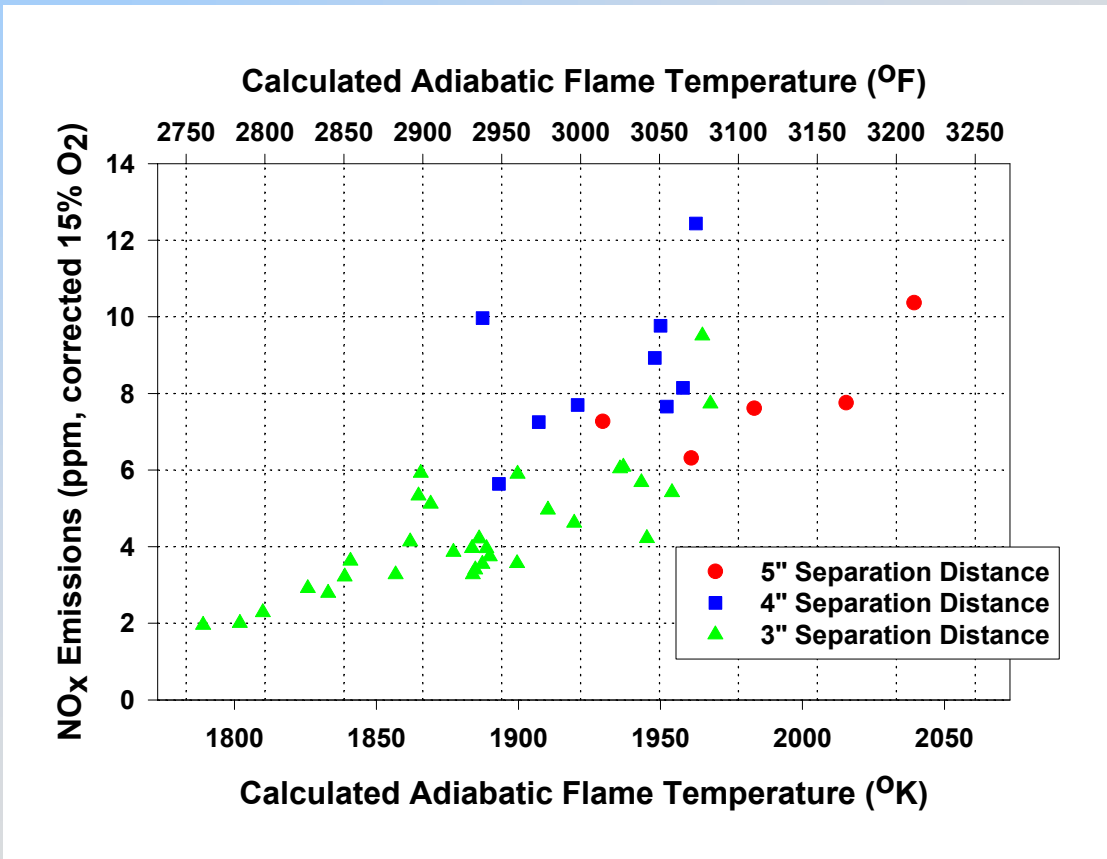
Before

After

Injector number One before and after testing.

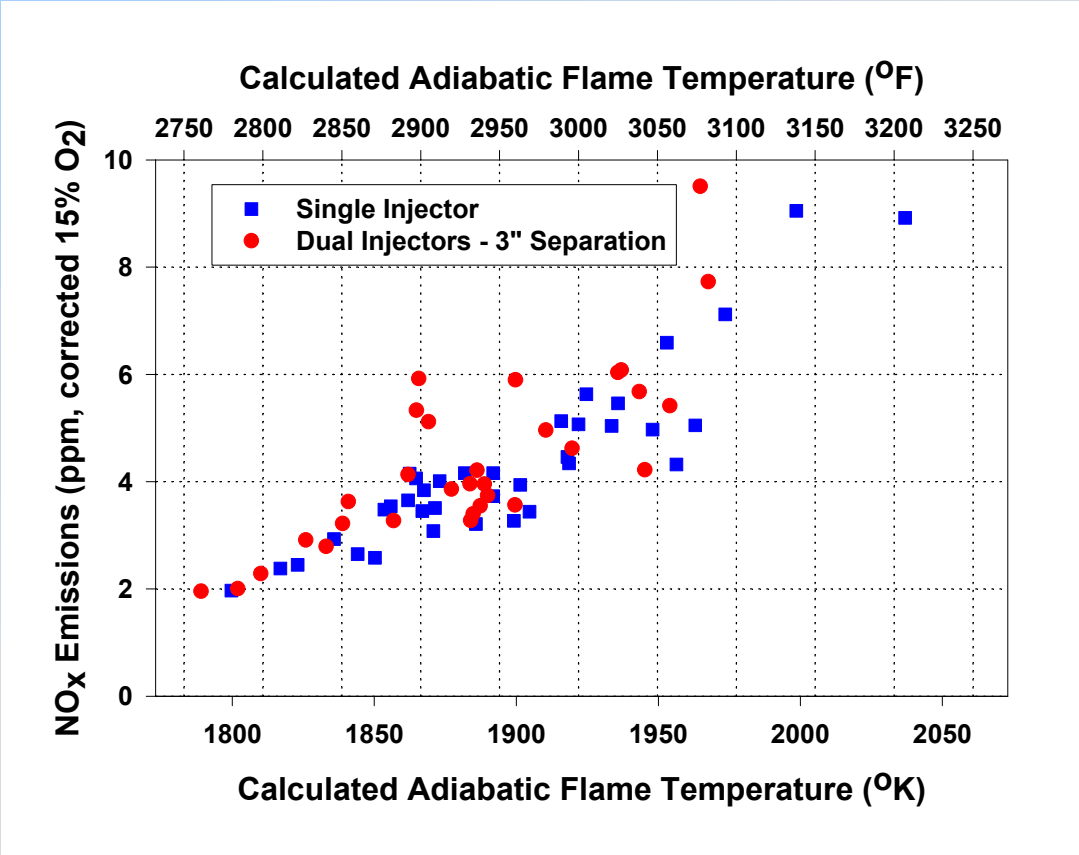
- Color change due to oxide formation
- No signs of aging
- No damage to metal fiber structure
- No evidence of over heating

Sector Rig Results



NO_X Emissions for Both Injectors Fired

Sector Rig Results



NO_X emissions compared with previous results

Sector Rig Summary

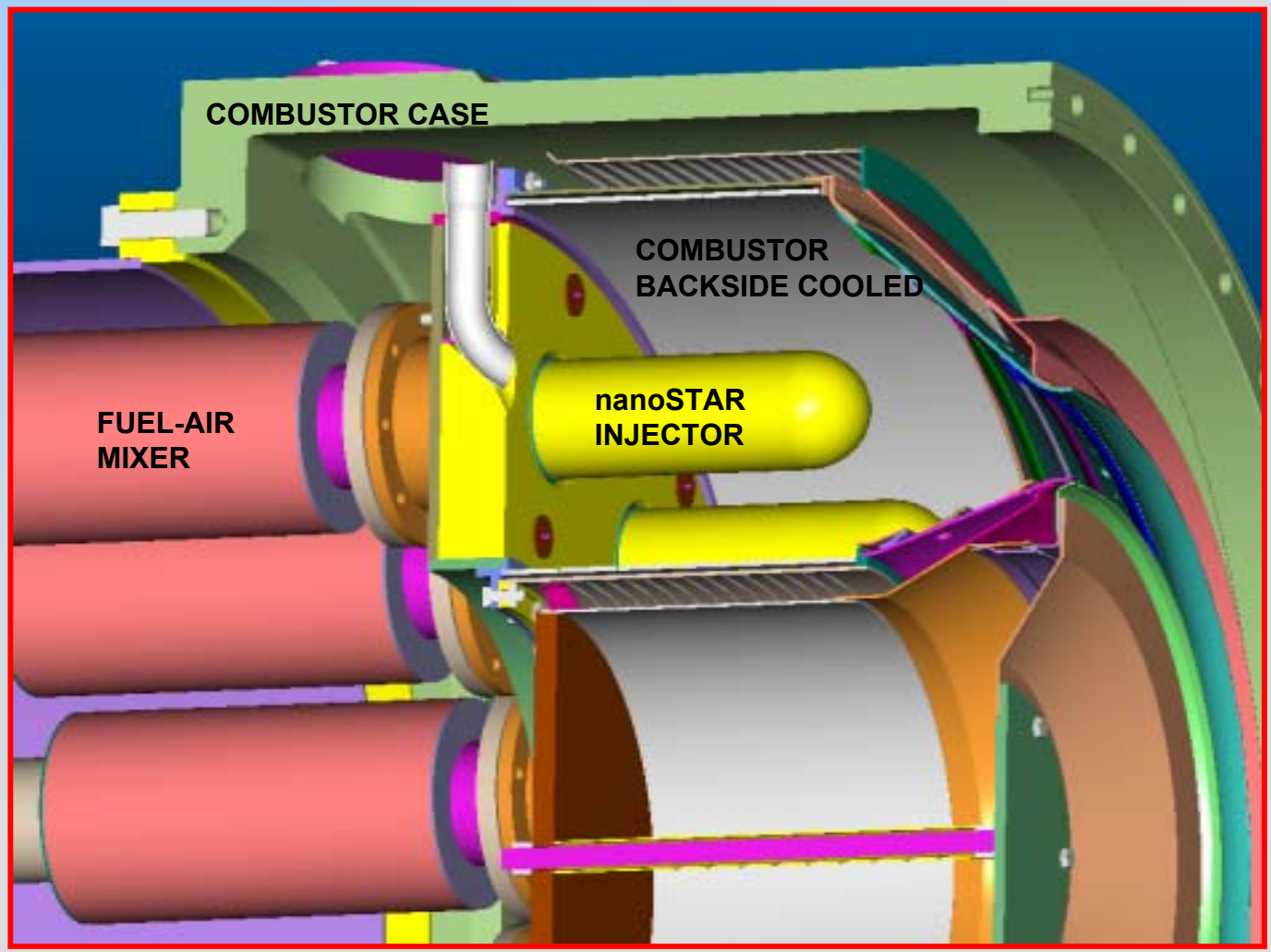
- Sustainable operation at injector separation required for application in an engine without combustor modification
- Successful pressurized ignition without combustion dynamics
- No detrimental interaction between injectors
- No accelerated aging
- Ultra-low NO_X emissions consistent with single injector tests
- Improved emissions performance under higher pressure and preheat operation

Full Scale Tests

Objectives

- Manufacture set of 12 burners and mixers
- Demonstrate ultra-low NO_x at simulated full load
- Demonstrate short-term hardware durability
- Demonstrate ignition characteristics
- Assess Pattern factor and temperature profile (atmospheric only)
- Identify and quantify any pressure oscillations
- Identify potential CO and HC combustor residence time issues

Full Scale Tests



Full Scale Tests Manufacturing

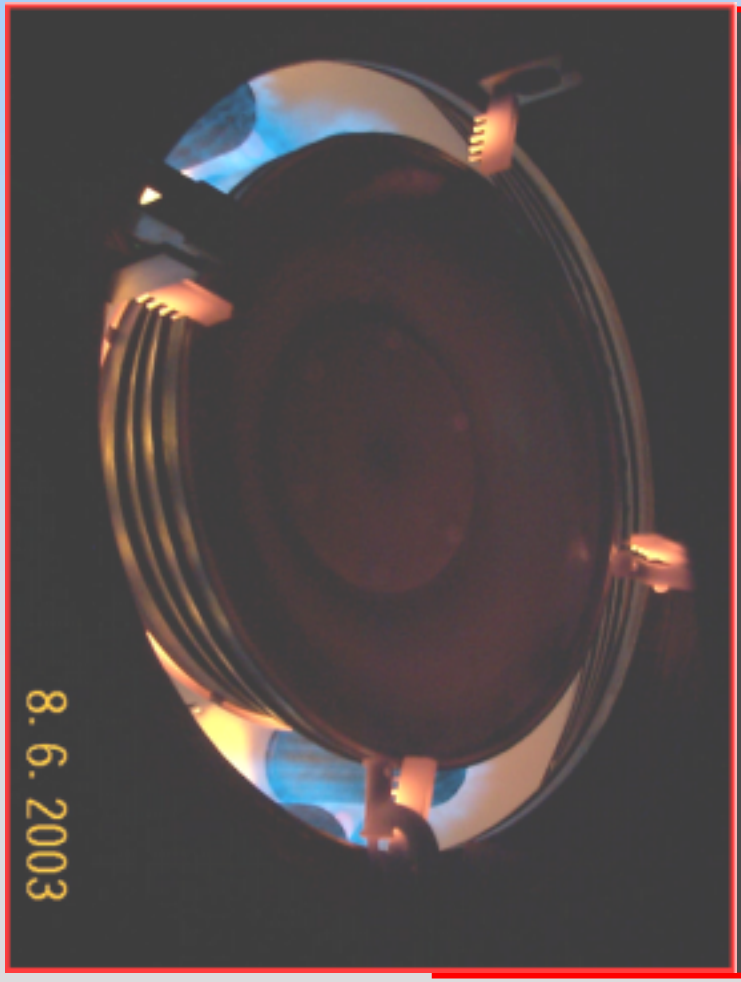
- Pre-production prototype manufacturing demonstrated
  - Injector head, internal distributor & mixer
  - 12 injectors (+ 2 spares) delivered for Full Scale Rig Testing
  - All parts within QC specifications

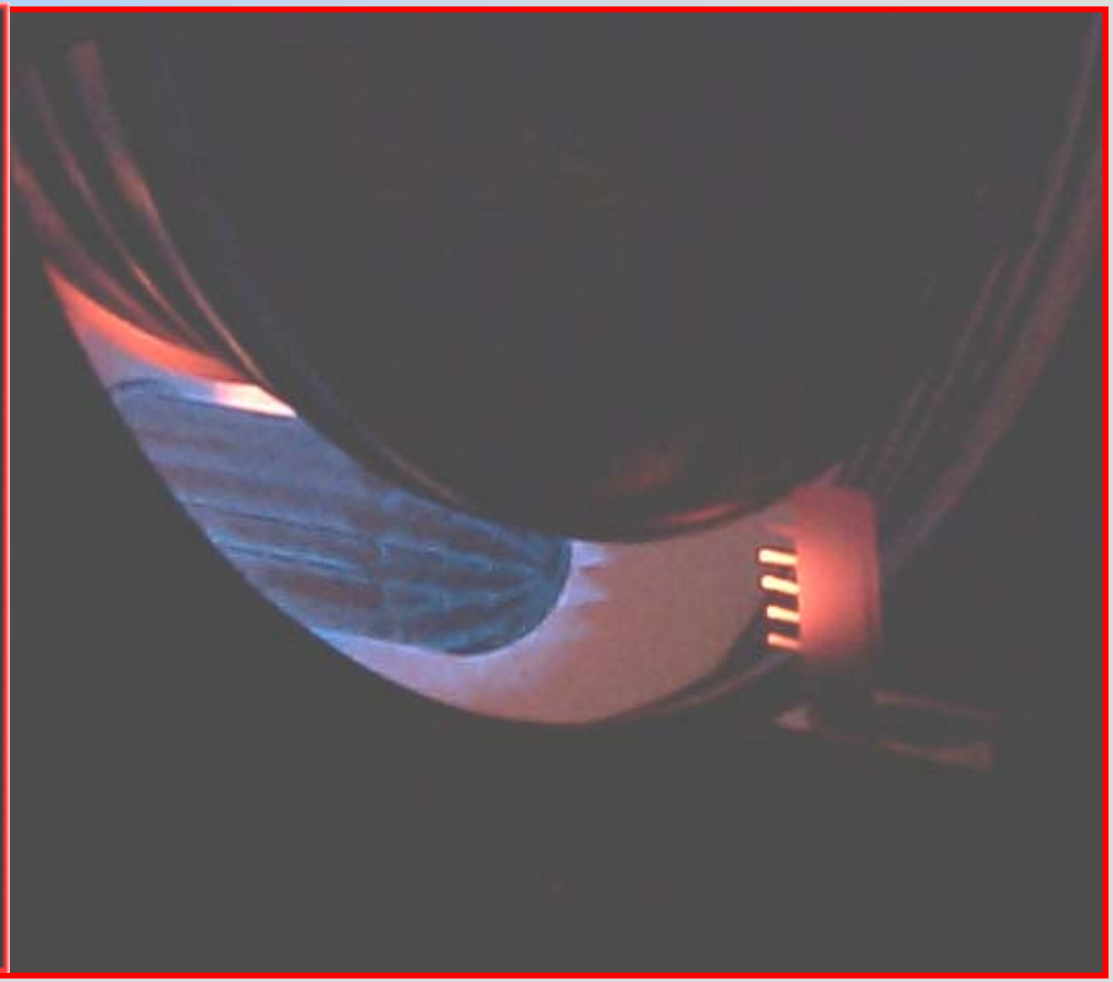
Full Scale Tests Manufacturing

nanoSTAR		CTC Injectors		Standard		Pass/ Fail
		Value	σ	Min	Max	
Pad Mass	gm	110.8	2.0	105	115	PASS
Surface Area	in^2	59.3	0.3	58.5	60	PASS
Flow Check						
Effective Area	in^2	1.144	0.006	1.135	1.155	PASS
DP/P		1.045	-	1.043	1.047	PASS

Full Scale Tests Hardware

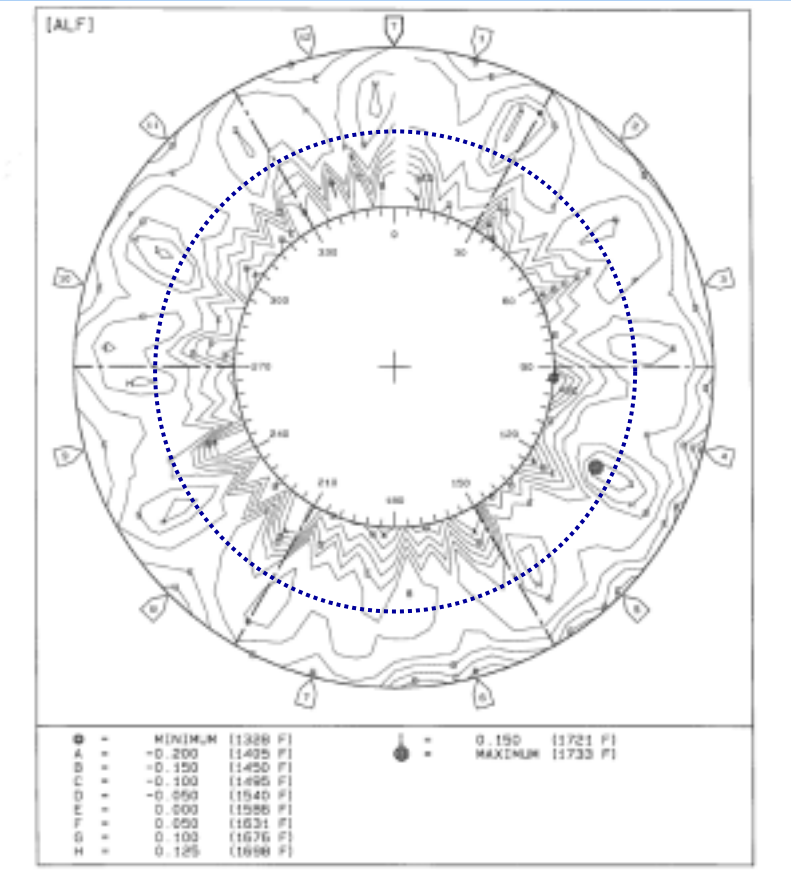
Full Scale Tests
Atmospheric Results

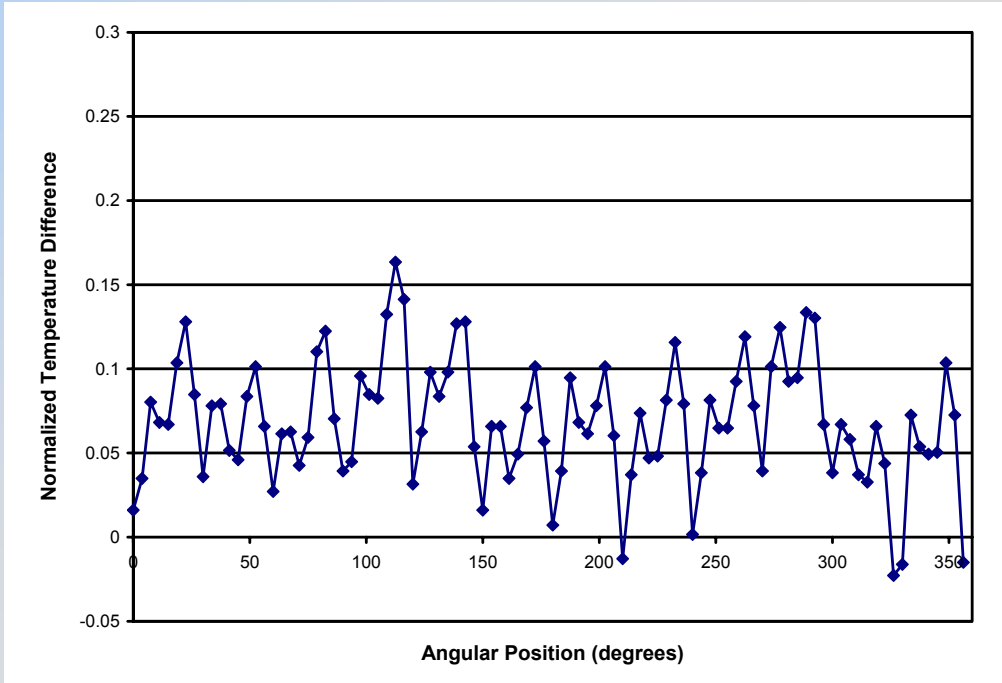




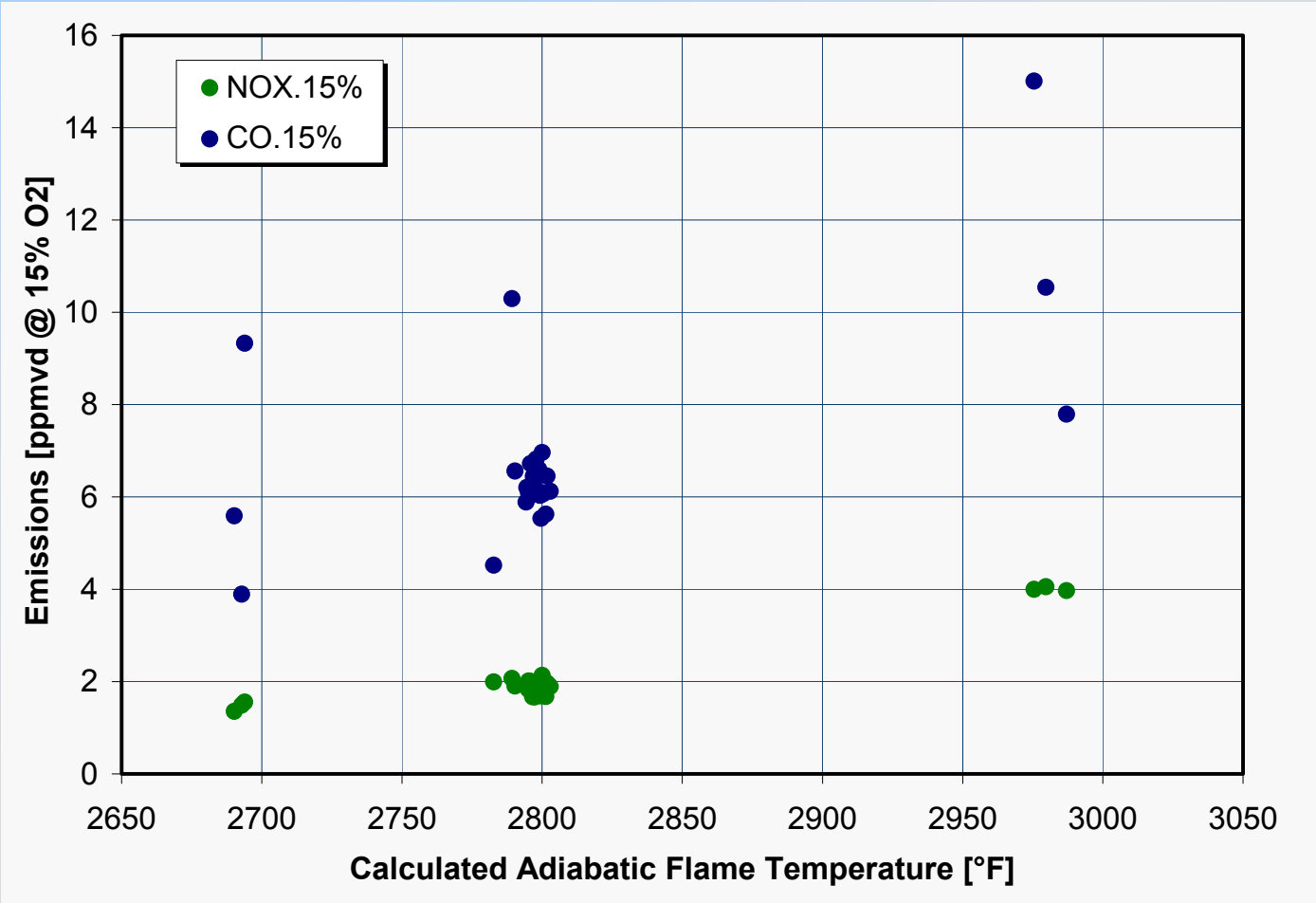
Full Scale Tests
Atmospheric Results

Pattern Factor Testing



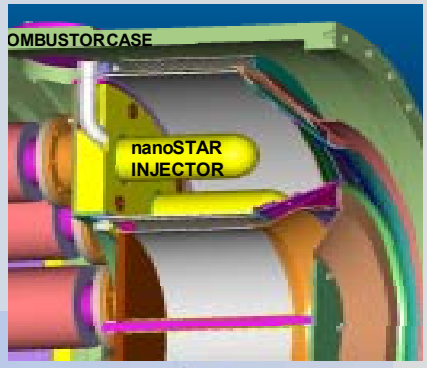


Full Scale Tests
Atmospheric Results

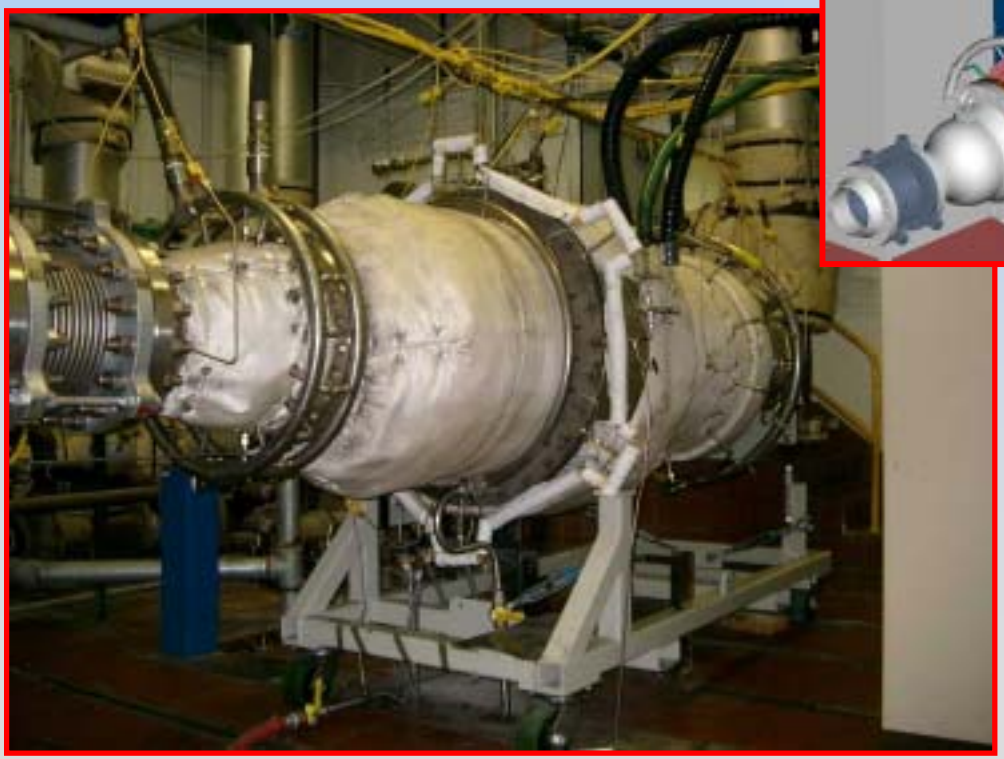


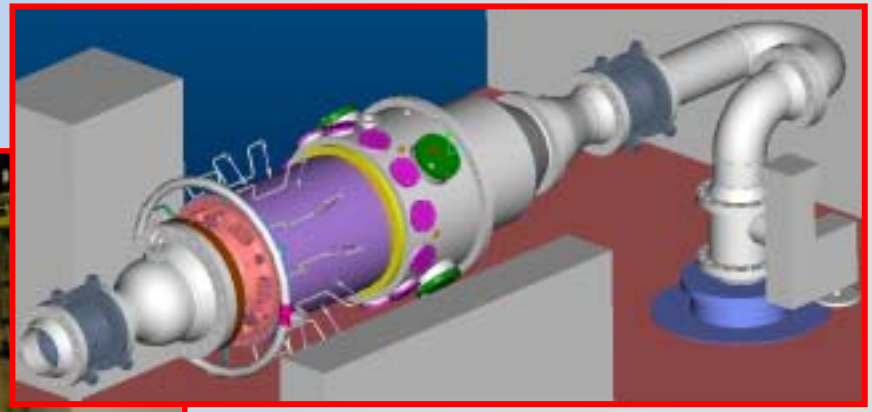
Full Scale Tests
Atmospheric Summary

- Atmospheric Test
  - Low pattern factor
  - Acceptable radial profile
  - Quick, reliable ignition
  - No measurable combustion dynamics
  - Duplication of single injector emissions performance tests

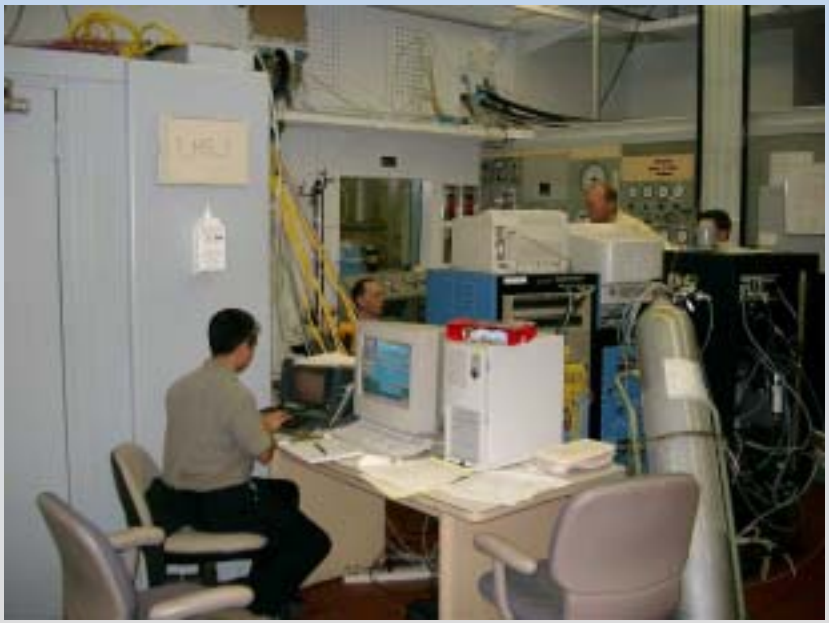


Full Scale Tests
Pressure Facility

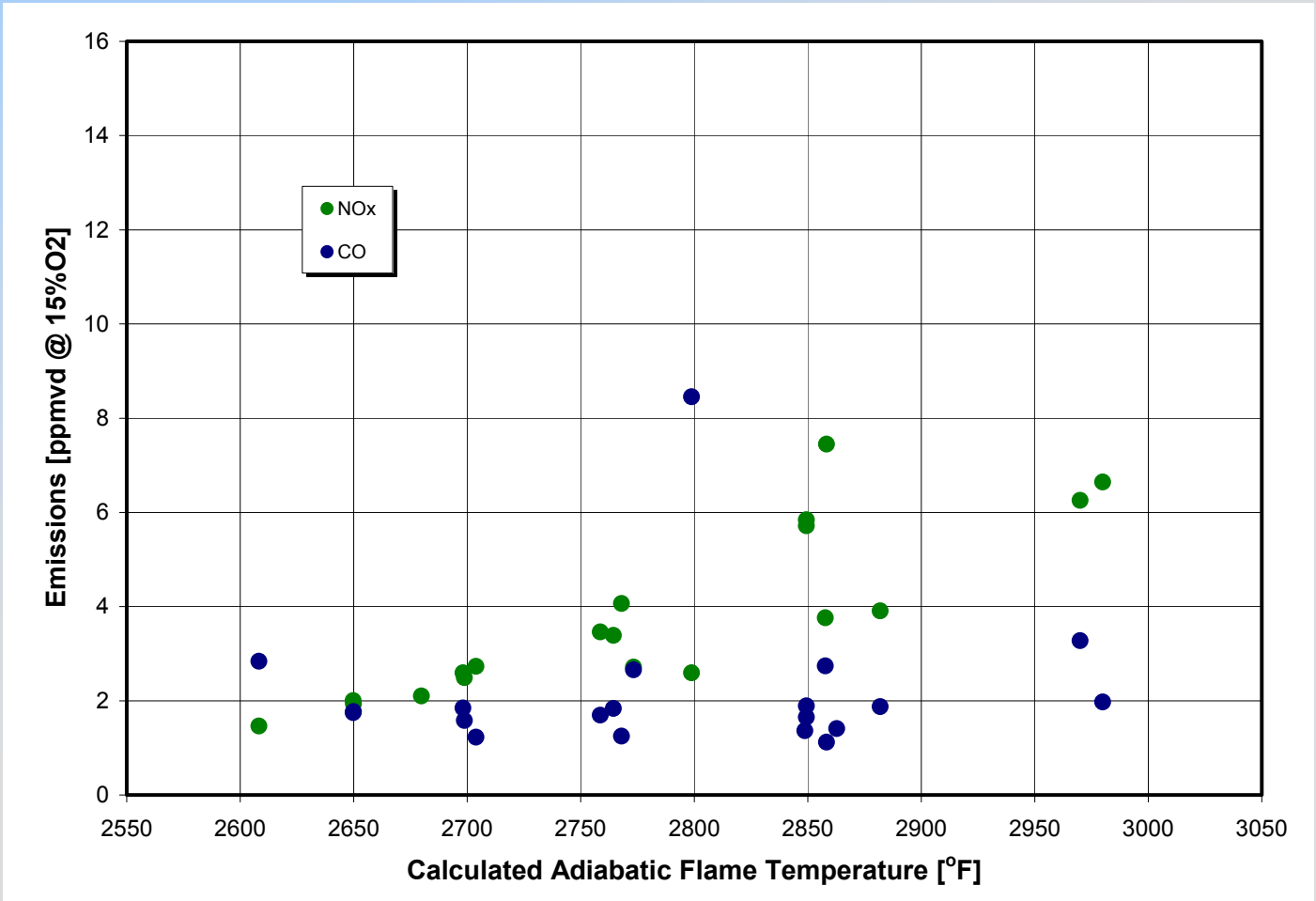




Full Scale Tests
Pressurized Results

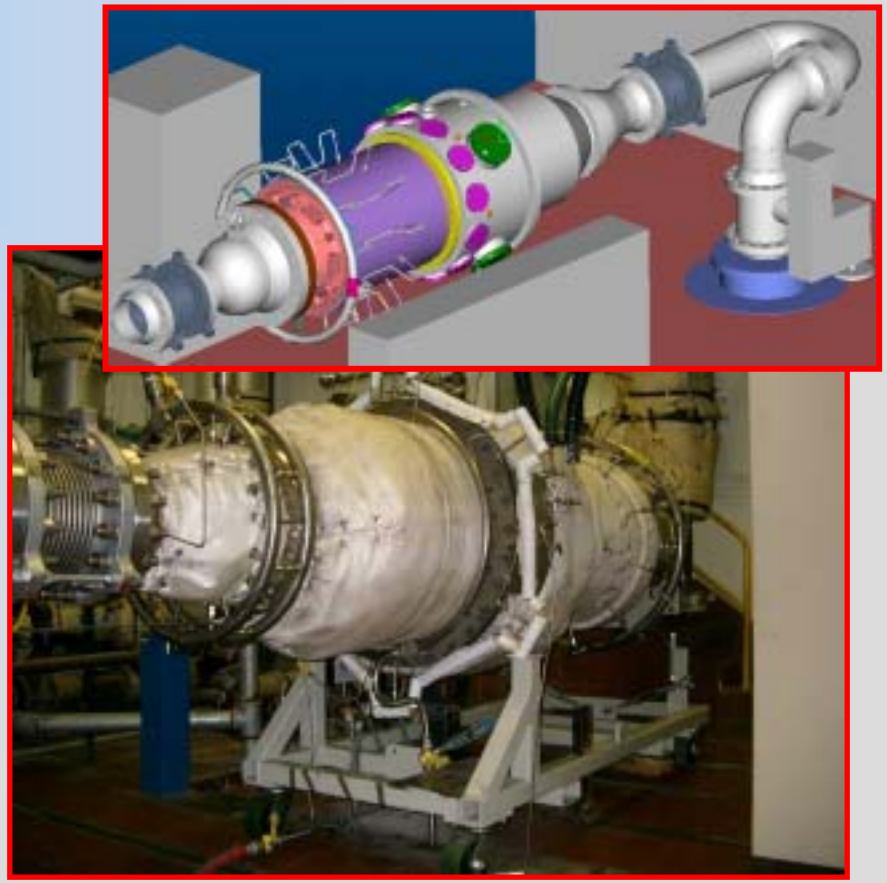


Full Scale Tests
Pressurized Results



Full Scale Tests
Pressurized Summary

- Pressurized Test - CTC
  - Excellent Emissions, < 2 ppm NOx and < 5 ppm CO
  - Quick, reliable ignition
  - No measurable combustion dynamics
  - Duplication of single injector emissions performance tests
  - Injectors damaged by over temperature event (fuel control)



Conclusions

- Successfully completed project milestones and have moved the nanoSTAR technology from proof-of-concept to full scale
- Injector technology has demonstrated low emissions (< 2 ppm NOx and < 5 ppm CO) performance at full scale
- Injector durability, system pressure drop, and ultimate life require further investigation
- Application of the technology to the Taurus 70 is planned for the next year with continued support from the California Energy Commission